

LHCb pentaquarks in constituent quark models

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The recently discovered $P_c(4380)^+$ and $P_c(4450)^+$ states at LHCb have masses close to the $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ thresholds, respectively, which suggest that they may have significant meson-baryon molecular components. We analyze these states in the framework of a constituent quark model which has been applied to a wide range of hadronic observables, being the model parameters, therefore, completely constrained.

The $P_c(4380)^+$ and $P_c(4450)^+$ are studied as molecular states composed by charmed baryons and open charm mesons. Several bound states with the proper binding energy are found in the $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ channels. We discuss the possible assignments of these states from their decay widths. Moreover, two more states are predicted, associated with the $\bar{D}\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ thresholds.

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One of the most important research topics of hadron physics in the last years has been the hadron structure beyond the naive quark model. Already in the dawn of the quark models, Gell-Mann suggested [1] that, apart from the popular $q\bar{q}$ and qqq configurations, there could exist multiquark structures.

Since 2003 plenty of new XYZ states were reported, being most of them candidates to multiquark configurations [2]. Among the last XYZ states discovered, the two charm pentaquark resonances $P_c(4380)^+$ and $P_c(4450)^+$ were observed by the LHCb Collaboration in the $J/\psi p$ invariant mass spectrum in the $\Lambda_b^0 \rightarrow J/\psi K^- p$ process [3]. The values of the masses and widths from a fit using Breit-Wigner amplitudes are $M_{P_c(4380)} = (4380 \pm 8 \pm 29) \text{ MeV}/c^2$, $\Gamma_{P_c(4380)} = (205 \pm 18 \pm 86) \text{ MeV}$, $M_{P_c(4450)} = (4449.8 \pm 1.7 \pm 2.5) \text{ MeV}/c^2$ and $\Gamma_{P_c(4450)} = (39 \pm 5 \pm 19) \text{ MeV}$.

According to the LHCb analysis the most likely angular momentum and parity values for the states are $J^P = \frac{3}{2}^\pm$ or $J^P = \frac{5}{2}^\pm$. The parities of the two states are opposite with the preferred spins being $\frac{3}{2}$ for one of the two states and $\frac{5}{2}$ for the other.

After the report of the two P_c^+ structures many theoretical works appeared suggesting different explanations, from the molecular meson-baryon pentaquark to kinematical triangle singularities going through diquark models or topological soliton models. As it is impossible, within the length of a letter, to cite all the publications we refer to the review [4].

A common characteristic of the pentaquark structures and the XYZ states is that they appear in the vicinity of a two particle threshold. For example, the $P_c(4380)^+$ and $P_c(4450)^+$ are very close to the $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ thresholds, respectively. This fact suggests that, if there exist a strong enough residual interaction between the two particles, a bound state or a resonance can be formed. The structure of these bound states depends on the dynamics of the two particle system and this dynamics is usually

model dependent. It is critical to have under control the strength of the residual interaction, because different structures can be produced depending on which threshold are involved in the dynamics of a potential bound state. For that reason, the interaction should be fully validated from the comparison against other experiments to avoid the generation of spurious bound states.

A model which fulfills the requirements stated above is the constituent quark model of Ref. [5], updated in Ref. [6]. The model has been extensively used to describe the hadron phenomenology [7–9].

The aim of this letter is to use this model to study the possible existence of charm pentaquark resonances in this energy region

The most natural explanation for the two pentaquark resonance is to assume a $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecular structure, where $(*)$ denotes any combination of \bar{D} (Σ_c) or \bar{D}^* (Σ_c^*) states. Other possible configurations like $\chi_{c1}p$, which have thresholds in this energy region, are less likely due to the lack of residual interaction at first order between the two particles. Taken into account that the J^P of the different states are not clearly determined in the experiment, it would be also interesting to calculate the strong decays of the pentaquark resonances, which can provide guidance to the experimentalists.

The constituent quark model of Ref. [5] is based on the assumption that the light constituent mass appears due to the spontaneous chiral symmetry breaking of QCD at some momentum scale. Regardless of the breaking mechanism, the simplest Lagrangian which describe this situation must contain chiral fields to compensate the mass term and can be expressed as [10]

$$\mathcal{L} = \bar{\psi}(i \not{\partial} - M(q^2)U^{\gamma_5})\psi \quad (1)$$

where $U^{\gamma_5} = \exp(i\pi^a \lambda^a \gamma_5 / f_\pi)$, π^a denotes nine pseudoscalar fields ($\eta_0, \vec{\pi}, K_i, \eta_8$) with $i = 1, \dots, 4$ and $M(q^2)$ is the constituent mass. This constituent quark mass, which vanishes at large momenta and is frozen at low momenta at a value around 300 MeV, can be explicitly

obtained from the theory but its theoretical behavior can be simulated by parametrizing $M(q^2) = m_q F(q^2)$ where $m_q \simeq 300$ MeV, and

$$F(q^2) = \left[\frac{\Lambda^2}{\Lambda^2 + q^2} \right]^{\frac{1}{2}}. \quad (2)$$

The cut-off Λ fixes the chiral symmetry breaking scale.

The Goldstone boson field matrix U^{γ_5} can be expanded in terms of boson fields,

$$U^{\gamma_5} = 1 + \frac{i}{f_\pi} \gamma^5 \lambda^a \pi^a - \frac{1}{2f_\pi^2} \pi^a \pi^a + \dots \quad (3)$$

The first term of the expansion generates the constituent quark mass while the second gives rise to a one-boson exchange interaction between quarks. The main contribution of the third term comes from the two-pion exchange which has been simulated by means of a scalar exchange potential.

In the heavy quark sector chiral symmetry is explicitly broken and we do not need to introduce additional fields. However the chiral fields introduced above provide a natural way to incorporate the pion exchange interaction in the molecular dynamics.

The other two main properties of QCD (besides the chiral symmetry breaking) are confinement and asymptotic freedom. At present it is still unfeasible to analytically derive these properties from the QCD Lagrangian, hence we model the interaction by a phenomenological confinement and the one-gluon exchange potentials, the last one, following De Rujula [11], coming from the lagrangian.

$$\mathcal{L}_{gqq} = i\sqrt{4\pi\alpha_s} \bar{\psi} \gamma_\mu G_c^\mu \lambda_c \psi, \quad (4)$$

where λ_c are the SU(3) color generators and G_c^μ the gluon field.

The confinement term, which prevents from having colored hadrons, can be physically interpreted in a picture where the quark and the antiquark are linked by a one-dimensional color flux-tube. The spontaneous creation of light-quark pairs may give rise at same scale to a breakup of the color flux-tube. This can be translated into a screened potential, in such a way that the potential saturates at the same interquark distance, such as

$$V_{CON}(\vec{r}_{ij}) = \{-a_c(1 - e^{-\mu_c r_{ij}}) + \Delta\}(\vec{\lambda}_i \cdot \vec{\lambda}_j) \quad (5)$$

where Δ is a global constant to fit the origin of energies. Explicit expressions for all these interactions are given in Ref. [5]. In the same reference all the parameters of the model are detailed, additionally adapted for the heavy meson spectra in Ref. [6].

Following Ref. [7], in order to model the meson-baryon system we use a Gaussian form to describe the baryon wave function,

$$\psi(\vec{p}_i) = \prod_{i=1}^3 \left[\frac{\alpha_i b^2}{\pi} \right]^{\frac{3}{4}} e^{-\frac{b^2 \alpha_i p_i^2}{2}}, \quad (6)$$

where we take the values $b = 0.518$ fm and $\alpha_i = 1$ for the nucleon wave function [7], and the scaling parameters α_i for different flavors are obtained using the prescription of Ref. [12].

In terms of Jacobi coordinates this wave function is expressed as,

$$\psi = \left[\frac{\eta b^2}{3\pi} \right]^{\frac{3}{4}} e^{-\frac{b^2 \eta P^2}{6}} \phi_B(\vec{p}_{\xi_1}, \vec{p}_{\xi_2}) \quad (7)$$

where \vec{P} is the baryon momentum in the center of mass system and \vec{p}_{ξ_1} and \vec{p}_{ξ_2} momenta correspond to internal coordinates. The internal spatial wave function is written as,

$$\phi_B(\vec{p}_{\xi_1}, \vec{p}_{\xi_2}) = \left[\frac{2\eta_1 b^2}{\pi} \right]^{\frac{3}{4}} e^{-b^2 \eta_1 p_{\xi_1}^2} \left[\frac{3\eta_2 b^2}{2\pi} \right]^{\frac{3}{4}} e^{-\frac{3}{4} b^2 \eta_2 p_{\xi_2}^2} \quad (8)$$

To find the quark-antiquark bound states we solve the Schrödinger equation using the Gaussian Expansion Method [13] with the interaction described above.

The meson-baryon interaction is derived from the qq interaction by using the Resonating Group Method (RGM), introduced by Wheeler [14] to study light nuclei but also widely used to study multi-quark systems [15].

In our case, the meson baryon interaction under evaluation has a quark content $\bar{Q}n - Qnn$, where $Q = c, b$ and n are the light quarks. Due to the presence of these light quarks, a complete interaction for this system must include a direct potential V_D , generated by π and σ exchanges, and an exchange one, V_E . These potentials can be expressed as

$$V_D(\vec{P}', \vec{P}) = \sum_{i \in A; j \in B} \int \Psi_{l'_A m'_A}^*(\vec{p}'_A) \Psi_{l'_B m'_B}^*(\vec{p}'_B) V_{ij}^D(\vec{p}'_{ij}, \vec{p}_{ij}) \Psi_{l_A m_A}(\vec{p}_A) \Psi_{l_B m_B}(\vec{p}_B) dp'_{\xi_A} dp'_{\xi_B} dp_{\xi_A} dp_{\xi_B} \quad (9)$$

$$V_E(\vec{P}', \vec{P}) = \sum_{i \in A; j \in B} \int \Psi_{l'_A m'_A}^*(\vec{p}'_A) \Psi_{l'_B m'_B}^*(\vec{p}'_B) V_{ij}^E(\vec{p}'_{ij}, \vec{p}_{ij}) \Psi_{l_A m_A}(\vec{p}_A) \Psi_{l_B m_B}(\vec{p}_B) dp'_{\xi_A} dp'_{\xi_B} dp_{\xi_A} dp_{\xi_B} \quad (10)$$

which gives the residual interaction between clusters and, at the same time, describes the strong decays of the potential bound states into the different channels like $\bar{D}^{(*)}\Lambda_c$, with direct potentials, or $J/\psi N$, done by simple quark rearrangement driven by the quark interaction.

Exploiting the symmetries of the system there are six possible diagrams which contribute to this coupling. The h_{fi} matrix elements corresponding to each diagram is the product of three factors

$$h_{ij}(\vec{P}', \vec{P}) = S \langle \phi_{\bar{D}^{(*)}} \phi_{\Sigma_c^{(*)}} | H_{ij}^O | \phi_{\bar{D}^{(*)}} \phi_{\Sigma_c^{(*)}} \rangle \langle \xi_{\bar{D}^{(*)}\Sigma_c^{(*)}}^{SFC} | \mathcal{O}_{ij}^{SFC} | \xi_{\bar{D}^{(*)}\Sigma_c^{(*)}}^{SFC} \rangle \quad (11)$$

where S is a phase characteristic of each diagram, resulting from the permutation between fermion operators. This potential involves the same interquark interactions as the direct potentials, that is, π and σ interactions, plus

contributions of both, the OGE and confinement potentials.

The coupled channel equations are solved through the Lippmann-Schwinger equation for the t matrix

$$t^{\beta\beta'}(p, p', E) = V_T^{\beta\beta'}(p, p', E) - \sum_{\beta''} \int dq q^2 \frac{V_T^{\beta\beta''}(p, q, E) t^{\beta''\beta'}(q, p', E)}{q^2/(2\mu) - E - i0} \quad (12)$$

where β specifies the quantum numbers necessary to define a partial wave in the baryon meson state. Finding the poles of the $t(\vec{p}, \vec{p}', E)$ matrix we will determine the mass and the quantum numbers of the molecules.

The decay of the particle is calculated through the standard formula

$$\Gamma = 2\pi \frac{E_A E_B k_0}{M_{P_c}} \sum_{J,L} |\mathcal{M}_{J,L}|^2 \quad (13)$$

where E_A and E_B are the relativistic energies of the final state hadrons $\bar{D}^{(*)}\Lambda_c$ or $J/\psi N$, M_{P_c} is the mass of the pentaquark and k_0 is the on-shell momentum of the system, given by,

$$k_0 = \frac{\sqrt{[M_{P_c}^2 - (M_A - M_B)^2][M_{P_c}^2 - (M_A + M_B)^2]}}{2M_{P_c}}. \quad (14)$$

To calculate the final amplitude of the process \mathcal{M} the wave function of the molecular state is used,

$$\mathcal{M} = \int_0^\infty V_{\bar{D}^{(*)}\Sigma_c \rightarrow AB}(k_0, P) \chi_{\bar{D}^{(*)}\Sigma_c}(P) P^2 dP \quad (15)$$

where $V_{\bar{D}^{(*)}\Sigma_c \rightarrow AB}(k_0, P)$ is the potential to the final state and $\chi_{\bar{D}^{(*)}\Sigma_c}$ is the pentaquark wave function.

Exploring the most interesting channels for the $\bar{D}^{(*)}\Sigma_c^{(*)}$ we obtain the pentaquark candidates shown in Table I.

Molecule	J^P	I	$Mass(MeV/c^2)$	$B_E(MeV/c^2)$
$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	$\frac{1}{2}$	4320.782	0.765
$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	$\frac{1}{2}$	4384.993	0.993
$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	$\frac{1}{2}$	4458.894	3.796
$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	$\frac{1}{2}$	4461.284	1.406
$\bar{D}^*\Sigma_c$	$\frac{3}{2}^+$	$\frac{1}{2}$	4462.677	0.013
$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	$\frac{1}{2}$	4519.792	7.338
$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	$\frac{1}{2}$	4523.275	3.855
$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	$\frac{1}{2}$	4524.552	2.578
$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^+$	$\frac{1}{2}$	4526.165	0.965

TABLE I: Masses of the different molecular states

We consider the $\bar{D}^{(*)}\Sigma_c^{(*)}$ thresholds, which are the only ones where a sizable residual interaction can be expected, mainly due to the pion exchanges. As stated above, other structures like $\chi_{c1}p$ do not have, in our model, residual interaction at first order and, hence, it is unlikely that they can develop a pentaquark structure. In the mass region of the $P_c(4380)^+$ we obtain one $\bar{D}\Sigma_c^*$ state with $J^P = \frac{3}{2}^-$. Its mass is very close to the experimental one (note that the calculation performed to obtain this values is parameter free) and should, in principle, be identified with $P_c(4380)^+$.

Referring to the channel $\bar{D}^*\Sigma_c$ we found three almost-degenerated states around $M=4460$ MeV/ c^2 with $J^P = \frac{1}{2}^-$, $\frac{3}{2}^-$ and $\frac{3}{2}^+$. The existence of these three degenerated states may be the origin of the uncertainty in the experimental value of J^P . The energy of those states makes

Molecule	J^P	I	Width $J/\psi p$	Width $\bar{D}^* \Lambda_c$
$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	$\frac{1}{2}$	2.394	1.109
$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	$\frac{1}{2}$	10.046	14.688
$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	$\frac{1}{2}$	5.294	63.576
$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	$\frac{1}{2}$	0.794	21.198
$\bar{D}^*\Sigma_c$	$\frac{3}{2}^+$	$\frac{1}{2}$	0.214	6.292
$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	$\frac{1}{2}$	0.893	9.954
$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	$\frac{1}{2}$	22.901	4.050
$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	$\frac{1}{2}$	0.053	3.048
$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^+$	$\frac{1}{2}$	0.051	0.845

TABLE II: Widths, in MeV, of the different molecular states

them natural candidates for the $P_c(4450)^+$.

Finally, if we look to the $\bar{D}\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ channels, we found one state in the first channel with $J^P = \frac{1}{2}^-$ and four almost-degenerated states around 4523 MeV/ c^2 with $J^P = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$ and $\frac{5}{2}^+$. The first state is around 60 MeV/ c^2 lower than the one found in the $\bar{D}\Sigma_c^*$ channel but with different quantum numbers. The second four states are higher in energy than the $P_c(4450)^+$. Both may correspond to new pentaquark states.

In order to obtain a deeper insight into the structure of the pentaquarks we have studied the decay channels $J/\psi p$, the channel in which the resonances were discovered, and $\bar{D}^*\Lambda_c$. The corresponding widths for both channels are shown in Table II.

The first observation that can be made from these results is that the decay width through the $\bar{D}^*\Lambda_c$ channel is generally equal to or greater than the width via the $J/\psi p$ channel. This suggests that the $\bar{D}^*\Lambda_c$ channel is a suitable channel for studying the properties of these resonances. In particular, the width of the predicted $\bar{D}^*\Sigma_c$ resonance with $J^P = \frac{1}{2}^-$ is twelve times greater through the $\bar{D}^*\Lambda_c$ channel than through the $J/\psi p$ channel, being this decay a good check for the existence of the resonance.

The second observation is that the width of the $\bar{D}\Sigma_c^*$ $J^P = \frac{3}{2}^-$ state is too small to explain the experimental one, whereas the values of the widths in the $\bar{D}^*\Sigma_c$ are more compatibles with the experiment.

Concerning the parity of the states, a molecular scenario is not the most convenient to obtain positive parity states because, being the $\bar{D}^{(*)}$ mesons and the $\Sigma_c^{(*)}$ baryons of opposite parity, the relative angular momentum should be at least $L = 1$ (P-wave) which will be above S-waves. This is reflected in the fact that the states with positive parity in Table I are those with smaller binding energies.

The authors of Ref. [16] argued that, using the spin suggested by the experimental analysis, the most likely

assignment for spin parity of both pentaquarks are $J^P = (\frac{3}{2}^-, \frac{3}{2}^-)$ or $(\frac{3}{2}^-, \frac{5}{2}^+)$ and much less likely $(\frac{5}{2}^+, \frac{3}{2}^-)$. The first combination is present in our results although based on the decay widths our favorite combination would be $(\frac{3}{2}^-, \frac{1}{2}^-)$.

Although the two pentaquark states decaying to $J/\Psi p$ should have $I = \frac{1}{2}$, one could consider the possibility of $I = \frac{3}{2}$ pentaquarks decaying to $J/\Psi N \pi$ through a Δ . We have investigated this possibility and we did not find any such state.

Let us now compare our results with those of some other molecular models available on the literature. Roca *et al.* [17], using a coupled-channel unitary approach within the local hidden gauge formalism, found that the $P_c(4450)^+$ is a $\bar{D}^*\Sigma_c - \bar{D}^*\Sigma_c^*$ molecular state with $I = \frac{1}{2}$ and $J^P = \frac{3}{2}^-$. Although it seems similar to our result, a careful analysis shows that the binding energies predicted by this model are on the order of 45 MeV/ c^2 , whereas in our case the binding energies are always less than 10 MeV/ c^2 . This is the reason why a second $\bar{D}^*\Sigma_c^*$ component appears in Ref. [17]. In any case these differences are relevant to discriminate between the two models.

Using a model of meson exchanges combined with a Bethe-Salpeter equation, He [18] investigated different molecular channels. As in our case, He obtained a bound state with $J^P = \frac{3}{2}^-$ spin from the $\bar{D}\Sigma_c^*$ interaction, consistent with the $P_c(4380)^+$. From the $\bar{D}^*\Sigma_c$ channel a bound state with $J^P = \frac{5}{2}^+$ is produced, which can be related to the $P_c(4450)^+$. However, in order to obtain this last state, one has to move the cut-off from 1 GeV to almost 3 GeV.

Moreover, Chen *et al.* [19] obtained similar results to those of Ref. [17] in the framework of an OPE model, finding a $\bar{D}^*\Sigma_c$ molecular state with $(I = \frac{1}{2}, J^P = \frac{3}{2}^-)$ quantum numbers and a $\bar{D}^*\Sigma_c^*$ molecular state with $(I = \frac{1}{2}, J^P = \frac{5}{2}^-)$ in the same mass range that the observed $P_c(4380)^+$ and $P_c(4450)^+$ respectively. Again, the model should predict a strong residual interaction in order to lower the respective thresholds to the physical masses.

As a summary, our results confirm the fact that there are several states with a $\bar{D}^{(*)}\Sigma_c^{(*)}$ structure in the vicinity of the masses of the $P_c(4380)^+$ and $P_c(4450)^+$ pentaquark states reported by the LHCb. However, more theoretical and experimental work is needed to completely clarify the nature of these states.

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